NATIONAL RESEARCH COUNCIL
Division on Engineering and Physical Sciences
Board on Physics and Astronomy

Final Report
for the period
September 30, 2008 to June 30, 2014
to the
U.S. Department of Energy
on the

COMMITTEE ON ATOMIC, MOLECULAR AND OPTICAL SCIENCES

DE-FG02-08ER15953

The Committee on Atomic, Molecular, and Optical Sciences (CAMOS) is a standing activity of the National Research Council (NRC) that operates under the auspices of the Board on Physics and Astronomy. CAMOS is one of five standing committees of the BPA that are charged with assisting it in achieving its goals—monitoring the health of physics and astronomy, identifying important new developments at the scientific forefronts, fostering interactions with other fields, strengthening connections to technology, facilitating effective service to the nation, and enhancing education in physics. CAMOS provides these capabilities for the atomic, molecular and optical (AMO) sciences.

In particular, over the time period of this grant, CAMOS had the following objectives:

- To provide active stewardship of the agenda laid out in *Controlling the Quantum World*, the NRC decadal survey for AMO sciences;
- To provide a means for dialog with federal agencies on AMO sciences and related fields;
- To initiate case studies on important timely topics in AMO sciences and/or its multidisciplinary connections with other fields of science and technology.
- To provide a venue for discussion among AMO scientists and thereby provide a unifying force in this diverse and varied field.

Several mechanisms were developed to achieve these objectives. Its principal activities, developed to address the first, second, and fourth bulleted objectives, were two-day meetings that took place 1-2 times each year. At those meetings, it invited and engaged with representatives from a broad selection of federal agencies that support AMO sciences. For most of those meetings, it also conducted half-day focus sessions to determine the progress that had taken place since the release of that report in each of the frontier areas identified in the AMO decadal survey. Summaries of those focus sessions were prepared and made available to sponsoring agencies.

To address the third bulleted objective, CAMOS periodically developed proposals for more detailed consensus studies, workshops, and other types of activities. During the grant period, it successfully developed a proposal on intense ultrafast lasers and began work on the next AMO decadal survey. CAMOS's efforts to engage more widely with the AMO community included several outreach activities, including sponsoring a booth at the DAMOP meeting in 2010. Finally, from its position within the NRC's Board on Physics and Astronomy, CAMOS generally monitored advances in the physical sciences, technology, and engineering in order to identify important synergies with traditional AMO activities. More detailed descriptions of these activities are contained in the sections that follow.

The NRC appointed the following members to CAMOS, as of the end of the funding cycle -

Christopher Monroe, *Chair*, University of Maryland
Louis DiMauro, *Vice-chair*, Ohio State University
Gordon Baym, University of Illinois at Urbana-Champaign
Ali Belkacem, Lawrence Berkeley National Laboratory
Dmitry Budker, University of California at Berkeley
Kristan Corwin, Kansas State University
Paul Corkum, University of Ottawa
Brian DeMarco, University of Illinois
Ivan Deutsch, University of New Mexico
Todd Ditmire, The University of Texas
Roger Falcone, Lawrence Berkeley National Laboratory
Mette Gaarde, Louisiana State University
Anthony Johnson, University of Maryland
Robert Jones, University of Virginia
David H. Reitze, California Institute of Technology
Marianna Safronova, University of Delaware
David R. Schultz, Oak Ridge National Laboratory

Highlights of Meetings During the Grant Cycle

For the first four years of the funding cycle, CAMOS held two meetings per year. For the final two years of this funding cycle, CAMOS held a single meeting per year. The following discussion encapsulates the highlights of those meetings.

Spring Meeting – May 15-16, 2009

CAMOS held its first meeting after being reestablished in Washington DC at the NRC's Keck Center. Being the first meeting since the release of the AMO2010 survey of the field, *Controlling the Quantum World: The Science of Atoms, Molecules, and Light*, the meeting focused on the following issues:

- Hearing from the federal agencies on developments in their AMO programs since the release of the AMO2010 report and their assessments of the impact of the report.

- Discussing the opportunities for interagency synergy.
- Hosting a focus session on Quantum Information Science (QIS) that included assessing how CAMOS might assist in the identification of science opportunities enabled by developments in the implementation of quantum computing technologies. QIS was identified as a major research opportunity in the AMO2010 report.
- Developing the committee's agenda for the next year.

Fall Meeting – December 12-13, 2009

The fall 2009 meeting was held in Irvine, California. The principal focus of the meeting was on AMO science and energy, with the goal of assessing whether there is a possible opportunity for an NRC study on the contributions that AMO scientists can make in addressing the country's energy needs. The presentations began with an overview provided by committee member David Schultz (Oak Ridge National Laboratory) followed by a talk by David Fahey (National Oceanic and Atmospheric Administration) on the role of AMO sciences in atmospheric research. Victor Klimov (Los Alamos National Laboratory) then discussed some of the work being done in the Center for Advanced Solar Photophysics at LANL to better understand the physical principles for converting solar energy into electricity. That talk was followed by a presentation from Tim Sommerer, GE Research and Development, with a perspective from industry on how AMO science can contribute to work being done at GE in the area of low-temperature plasmas. The final speaker was Bill McCurdy (University of California at Davis), who discussed two developments in ultrafast experimental capabilities—high harmonic generation and free electron lasers—important tools for helping to develop a more complete understanding of some of the physical processes involved in energy sources and conversion. The committee then discussed opportunities for and the possible scope of an NRC study in this area. On the second day of the meeting, the committee discussed efforts that could be undertaken to generate interests in a study on quantum information science that the committee has been working on, and discussed ideas for other studies of possible interest to the AMO communities. Among the ideas discussed was intersectional work between AMO and condensed matter physics. The committee also discussed ways of increasing interactions between CAMOS and the broader community of AMO scientists, including possible activities at the next DAMOP meeting.

Spring Meeting – April 6-7, 2010

CAMOS held its spring meeting at the Keck Center in Washington, D.C., on April 6-7, 2010. The first day began with a focus session on connections between AMO and Condensed Matter physics. Presentations were given by Steve Girvin (Yale) on the convergence of condensed matter and cold atoms in areas such as optical lattices and optomechanical systems, by Phil Bucksbaum (Stanford) on connections in the regime of ultra-fast science, by Dan Stamper-Kurn (U.C. Berkeley) on his and others efforts to study condensed matter physics with ultracold atoms. The final speaker was Jose Onuchic (U.C. San Diego), who discussed his intersectional work of studying the physics of proteins. The morning session was followed by afternoon talks given by representatives of the federal agencies funding AMO research. Bob Dunford, NSF's AMO program director, highlighted some of the work funded by NSF, including research in quantum information science and energy and the environment. Jeff Krause, from DOE's Fundamental Interactions team, then spoke, discussing how the American Recovery and Reinvestment Act of

2009 (ARRA) provided the DOE's Office of Basic Energy Sciences the opportunity to invest over $550M in several activities, including an additional 16 Energy Frontier Research Centers. Among the highlights in DOE's FY2011 budget request are investments in an energy hub focused on Batteries and Energy Storage and in early career awards and graduate level fellowships. The final speaker was Tatjana Curcic, from the Air Force Office of Scientific Research. Dr. Curcic indicated that AFOSR's core research budget for FY10 was $321M with an additional $132M for the University Research Initiative. Their AMO program currently is focusing on cold/ultracold quantum gases, ultrafast/ultra-intense laser science and quantum information science. On the second day of the meeting, the committee reviewed efforts undertaken to promote the quantum information science proposal put together by the committee and the proposal developed regarding AMO science and energy. The committee also discussed possible other studies that might be of interest to the AMO community.

Fall Meeting – October 16-17, 2010

CAMOS's Fall meeting was held at Biosphere 2 in Oracle, Arizona over the weekend of October 16-17, 2010. The focus of the meeting was on precision measurements and fundamental laws, one of the areas highlighted in the 2010 AMO decadal survey as having great scientific promise. Most of the talks focused on the use of AMO techniques to address issues that are typically the domain of high energy physics. Two experimentalists spoke, CAMOS committee member Norval Fortson (University of Washington) and Jerry Gabrielse (Harvard) as did two theorists, Jonathan Sapirstein (Notre Dame) and Peter Graham (Stanford). Peter Graham began the presentations by discussing efforts to develop an atomic gravitational wave interferometric sensor (AGIS) for installation either in an underground site such as DUSEL or in a satellite configuration, with sensitivities to gravitational waves down to 1 Hz for terrestrial based studies and to 0.3 Hz for space-based studies. Dr. Graham then discussed some preliminary work in developing techniques to use molecular interferometry to detect axion dark matter. Jerry Gabrielse then provided his perspectives on some of the outstanding issues and interesting work in using precision rather than energy to probe fundamental science questions and included in his discussion current work in measuring the electron magnetic moment and determining the fine structure constant. He also noted that for researchers in these areas further advances require new methods of study that take time and sustained funding to develop and that working in an interdisciplinary area such as this produces challenges not faced by researchers whose work is more squarely in an established field such as AMO or high energy. Jonathan Sapirstein then spoke about theoretical work taking place whereby atomic physics is being used to test aspects of the Standard Model. Topics included recent extensions of quantum electrodynamics from one electron atoms to the whole periodic table, using atomic electric dipole moment calculations to test weak interactions, and testing strong interactions by evaluating the influence of the nucleus on atomic structure. The final speaker, Norval Fortson, discussed several topics, including the current state of atomic parity non-conservation experiments and current and planned electric dipole moment (EDM) experiments that will be used to test for theories beyond the standard model. On the second day of the meeting, the committee discussed several study proposals under development and the writing of short summaries on scientific topics covered by the decadal study.

Spring Meeting – April 5-6, 2011

CAMOS held its spring 2011 meeting at the Keck Center in Washington, D.C. on April 5-6, 2011. The first day began with a focus session on the science enabled by the latest generation of high-peak-power, ultrafast light sources, another area discussed in the 2010 AMO decadal study as having great scientific promise. Lou DiMauro (Ohio State University) began by speaking about advances in ultra-fast light pulses and some of the challenges in breaking the femtosecond barrier for pulses, as well as some of the frontier research taking place using sub-femtosecond pulses. Linda Young (Argonne National Laboratory) then discussed some of the AMO-related studies taking place using the X-ray free-electron laser at the SLAC Linac Coherent Light Source (LCLS). Included among those results were the production of multiple inner-shell photo-ionized "hollow" neon atoms and multiple inner-shell holes in diatomic and polyatomic molecules; the study of exploding clusters; and the initial diffraction diagnosis of protein nanocrystals. The third speaker at the focus session was Wim Leemans (Lawrence Berkeley National Laboratory), who discussed improvements in plasma-based electron accelerators, followed by Farhat Beg (University of California at San Diego), who spoke of recent advances in developing short-pulse high-intensity lasers for interactions with solid materials. Potential applications include fast ignition inertial confinement fusion, GeV plasma-based particle accelerators, proton sources for medical applications and neutron sources. The final speaker was CAMOS members Todd Ditmire (University of Texas at Austin), who discussed some of the research potentials associated with the development of lasers having peak powers beyond 1 picowatt.

The morning session was followed by afternoon talks given by representatives of federal agencies funding AMO research. Joe Dehmer, NSF's Physics Division director, highlighted some of the work funded by NSF, including the status of the physics frontiers centers and some of the goals that are guiding NSF's Physics programs. Tatjana Curcic, from the Air Force Office of Scientific Research (AFOSR) spoke next, discussing AFOSR's research program for AMO physics, and was followed by Jeff Krause, from DOE's Fundamental Interactions team. Dr. Krause presented an overview of the program and budgets for DOE's Office of Basic Energy Sciences (BES) and discussed the AMO program in those contexts, providing information about the composition and portfolio of the AMO program. The final speaker was Paul Baker, from the Army Research Office (ARO), who discussed their AMO program. On the second day of the meeting, the committee reviewed the status of several of the proposals that CAMOS has produced and possible other steps that CAMOS, either alone or in conjunction with other NRC standing committees, would be of benefit and interest to the AMO community.

Fall Meeting – October 3-4, 2011

CAMOS's Fall 2011 meeting was held at the Keck Center of the National Academies in Washington, D.C. on October 3-4, 2011. In carrying out its continuing responsibility to provide active stewardship for the AMO sciences' decadal survey, *Controlling the Quantum World*, the committee held a focus session on one of the areas highlighted in that report as having great scientific promise-nanoscale science. The committee heard from five speakers: Paul Weiss (University of California, Los Angeles), Vladimir Shalaev (Purdue University), Ray Beausoleil

(HP Laboratories), Konrad Lehnert (JILA), and Luke Lee (University of California, Berkeley). The speakers provided updates on five topics - nanoelectronics, metamaterials and plasmonics, applications of nanophotonics to information technology, nanomechanical oscillators, and applications of nanophotonics to biological physics. Many of the speakers noted the cross-disciplinary nature of the work that is taking place in these fields and also how this work has close ties and makes contributions to research in other areas of AMO science. More detailed information about the presentations and the discussion that took place following those presentations among committee members and speakers can be found in the summary prepared following the meeting, a link to which is provided in the list of Outreach Activities below.

On the second day of the meeting, the committee discussed several study proposals under development on high intensity lasers and quantum information sciences, and in particular, the potential audiences for those studies and recent developments in those fields that contribute to the need for such studies. The committee also discussed its makeup and possible new members, as well as the nature of the short summaries it prepares on the scientific topics covered by the decadal study.

Spring Meeting – April 3-4, 2012

CAMOS held its spring 2012 meeting at the Keck Center in Washington, D.C. on April 3-4, 2012. The first day began with a focus session on quantum control, another area discussed in the 2010 AMO decadal study as having great scientific promise. Herschel Rabitz, Princeton University, began the session by providing some general considerations on optimal control in chemistry, some of the implications of those efforts for other areas of science, as well as potential applications. Marcus Dantus (Michigan State University) then spoke about using phase control of pulsed laser light to study and manipulate chemical states. After discussing progress that has taken place in wave packet manipulation, he outlined some current applications that include studying chemical reactions, developing coherent control of electronic states and transitions, and determining the role that similar processes take in nature. The committee then heard from Thomas Weinacht (State University of New York in Stony Brook), who discussed work on strong-field control of molecular ionization and dissociation by using shaped ultrafast optical pulses. Committee member Tamar Seideman (Northwestern University) then discussed efforts to coherently align complex systems using moderately intense laser fields and some of the potential uses of this technique, such as assisting in molecular assembly and providing more control in efforts to study the nature and behavior of such systems and how they engage with their environment. The final speaker, Mikhail Lukin (Harvard University), discussed work involving the control of nitrogen vacancies in diamond, which provides a robust solid-state/atom hybrid system for manipulation and control. Potential applications being explored include use of the spins in the nitrogen vacancies as solid-state qubits and as probes in biological systems.

Following the quantum control session, the committee heard from representatives of agencies that support AMO physics. Wendell Hill discussed some of the goals of NSF's program, including centers having AMO focus, as well as efforts at the NSF to encourage cross-disciplinary work. Jeff Krause then discussed the short-term outlook for Basic Energy Sciences funding at DOE, including some of the upgrades being planned for or are underway at facilities

such as LCLS that. Riq Parra then spoke about the Air Force Office of Scientific Research's AMO program, including recent reorganization efforts that are geared towards making interaction between programs easier. Finally, Jamil Abo-Shaeer discussed DARPA research program in the AMO area, including work on sensors, the use of radiation pressure for cooling and heating, and optical lattice emulators. On the second day of the meeting, the committee reviewed the status of several of the proposals that CAMOS has produced and possible other steps that CAMOS, either alone or in conjunction with other NRC standing committees, would be of benefit and interest to the AMO community. These include the possible development of a brochure highlighting some of the work in selected fields of AMO.

Fall Meeting – October 1-2, 2012

CAMOS's Fall meeting was held at the Beckman Center of the National Academies in Irvine, California on October 1-2, 2012. Much of the meeting was spent on a potential brochure that discusses opportunities in quantum information and ultrafast sciences, two areas identified in the decadal survey for AMO sciences as particularly promising. The remainder of the meeting involved a focus session on industrial applications of atomic, molecular, and optical sciences. The first speaker was Mark Kasevich, from Stanford University. Dr. Kasevich discussed work underway in his laboratory that uses atom interferometry as extremely sensitive sensors. By measuring the relative phase shifts in the de Broglie waves of cold atoms, the sensors are able to directly read angular and linear displacements, which can then be used in accelerometers and gyroscopes. Among the many applications envisioned for such devises are GPS-free precision navigation, network time synchronization and, in the geodesic regime, the measurement of earthquake hazards and oil and mineral surveys. Dr. Kasevich also noted that there are a number of potential uses in basic science, including low-frequency gravitational wave detection, tests of general relativity, and measurements of the time variation of fundamental constants. The second speaker was Mike Anderson, from Vescent Photonics, Inc., located in Boulder, Colorado. Dr. Anderson discussed a number of products that Vescent has under development or on the market. These include compact diode laser systems that can be used by scientists and engineers for locking, as shutters, and for wavelength references. Other products include liquid-crystal waveguides and electro-optic beam steerers that have a number of potential applications in the communications and other fields.

Spring Meeting – April 2-3, 2013

CAMOS held its spring 2013 meeting at the Keck Center in Washington, D.C. on April 2-3, 2013. The first day began with talks by representatives of agencies that support AMO physics. NSF's Siu Au Lee and Ann Orel began the discussion by going over NSF's budget for AMO sciences in recent years and the role that priority programs and budgets play in their portfolio. The integrated Computational and Data-Enabled Science and Engineering (CDS&E) program was mentioned, as well as the recent NRC report on optics and photonics, which they note might generate a priority area for funding. DOE's Jeff Krause then discussed AMO physics and its role in the Office of Basic Energy Sciences at DOE. Much of the focus of his presentation and the discussion that followed was on funding trends and the impact of sequestration on budgets. As of the time of the meeting, the impact on individual programs of the recently passed budget for

the remainder of FY2013 had not been established. Riq Parra then spoke about the Air Force Office of Scientific Research's AMO program. Much of his discussion focused on AFOSR's Basic Research Initiative program, through which new areas of research are identified and funded. Paul Baker, from the Army Research Office and Jamil Abo-Shaeer, from DARPA, then discussed their programs, focusing on their efforts to expand their programs and pursue new initiatives. Finally, David Moehring, from IARPA, discussed his program, which has a strong focus on quantum information science.

The afternoon consisted of a focus session on quantum foundations. Alan Aspuru-Guzik, Harvard University, began by discussing some of his work in studying excitonic systems that seeks to provide insight into how light-harvesting in photosynthesis occurs. Among the unanswered questions in this field are the roles that quantum coherence and quantum transport play in the process of converting light into excitations of the biological systems, which is a focus of his work. Philip Pearle, Hamilton College, then spoke about his theoretical work that seeks to incorporate into the theoretical description of quantum dynamics a term that describes the collapse of a system into a specific state. His approach is to add to Schrodinger's equation a collapse Hamiltonian that describes, through a probability equation, the process by which a system collapses. Several examples were given that can be used to test the validity of this approach. The final speaker was Alipasha Vaziri, from the University of Vienna. Dr. Vaziri discussed his efforts in studying the dynamics of coupled biological systems, and in particular, how stochasticity, correlations, and coupled state dynamics contribute to the functions of biological systems and networks.

On the second day of the meeting, the committee met in closed session where it continued discussions on the development of a brochure highlighting work in selected fields of AMO and reviewed the status of several study proposals developed by CAMOS.

Spring Meeting – April 7-8, 2014

CAMOS held its annual meeting at the Keck Center in Washington, D.C. on April 7-8, 2014. The first day began with a session on the National Photonics Initiative. Alan Willner, University of Southern California, discussed the recently released NRC report - *Optics and Photonics: Essential Technologies for our Nation*, briefly going through some of the findings and recommendations, and the positive response that has been received so far from sponsors, industry, and members of the optics community. Phil Bucksbaum, Stanford University, and Tom Baer, Stanford University, then discussed the National Photonics Initiative, a response by professional socieities and industry to some of the recommendations in the report.

This next session consisted of talks by representatives of agencies that support AMO physics. Prem Kumar and Matt Goodman, from DARPA, led off the talks, discussing reorganizations that have taken place at DARPA and it's impact on some of their AMO projects. Riq Parra and Tatjana Curci then spoke about the Air Force Office of Scientific Research's AMO program. Among the big themes discussed was quantum simulation and a new MURI on quantum transducers. NSF's Ann Orel and John Gillaspy then went over NSF's budget for AMO sciences in recent years and noted that mid-scale will be receiving some emphasis. DOE's Jeff Krause

then discussed AMO physics and its role in the Office of Basic Energy Sciences at DOE. Much of the focus of his presentation and the discussion that followed was on funding trends and the impact that legislation requiring full funding of awards might have on programs. Jeff also discussed the recompetition that the EFRC's are going through. Paul Baker, from the Army Research Office then discussed his program and efforts he is undertaking to expand his program and pursue new initiatives. Finally, David Moehring, from IARPA, discussed his program, with its strong focus on quantum information science.

On the second day of the meeting, the committee met in closed session where it heard about the status of several proposals that CAMOS has been involved in developing (discussed in more detail in the section headed Study Proposals) and began discussions on developing the proposal for the next AMO decadal survey.

Study Proposals

In carrying out its responsibilities to initiate case studies on important timely topics in the AMO sciences, during the current grant cycle CAMOS developed a white paper on Opportunities in the Science, Applications, and Technology of Intense Ultrafast Lasers. Representatives of CAMOS and NRC staff discussed the proposal with representatives of several programs at DOE, NSF, AFOSR, and ONR, and received indications of strong support for the proposal. Formal proposals were prepared and submitted to those agencies that showed interest in the proposal. That study is now underway.

In addition, representatives of CAMOS and NRC staff developed and informally discussed with potential sponsors another white paper on quantum information sciences. So far, the agencies have declined to support that study. Finally, CAMOS has begun development of the proposal for the next decadal survey for AMO sciences, which is expected to be underway by the end of 2015.

Outreach Activities

As part of its efforts to reach the larger AMO community, CAMOS maintains a website at which it makes available to the public the presentations made at its meetings, as well as written summaries of the focus sessions at those meetings on topics of current interest. That material is available for download at - http://sites.nationalacademies.org/BPA/BPA_048649.

In addition, as part of an effort to increase communication with members of the AMO community and to more widely disseminate information about CAMOS' activities, CAMOS sponsored a booth at the annual meeting for the APS' Division of Atomic, Molecular and Optical Physics (DAMOP), held in Houston, Texas from May 25-29, 2010. BPA staff and CAMOS members were present to answer questions from DAMOP participants and to provide material to interested parties, including brochures about CAMOS, copies of the AMO decadal survey report and summary, as well as other reports recently generated by the BPA of interest to the AMO community.

Summary

This report is the final report for the 2008-2014 cycle of DOE support for the Committee on Atomic, Molecular, and Optical Sciences. Highlights of the committee's activities over this period included:

- Meetings of the committee were held semiannually (Washington, DC in April and Irvine, CA in October) for four of the six years and annually the last two years (Washington, DC in April).
- Committee meetings included half-day focus sessions on each of the areas identified in the last AMO decadal survey as having great scientific promise and short summaries of the focus session were prepared and delivered to sponsoring agencies.
- CAMOS initiated a study that has been funded on high intensity lasers.

DOE support for CAMOS has been of central importance to the committee's ability to continue to fulfill its mandate to the Board on Physics and Astronomy and to the wider atomic, molecular, and optical sciences research community.